ENGINEERING MATERIALS TECHNOLOGY
Structure, Processing, Properties & Selection

SECOND EDITION

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As authors we are indebted to the many people whose constructive suggestions and cooperation helped bring this book to completion. However, most of all, we dedicate this book to our wives, Martha and Virginia, and daughters, Sherri, Tammi, Jeanene, Liz, and Suzy, to all of whom we owe a major debt for their understanding, unfailing support, optimism, and tangible assistance as we toiled for many years.

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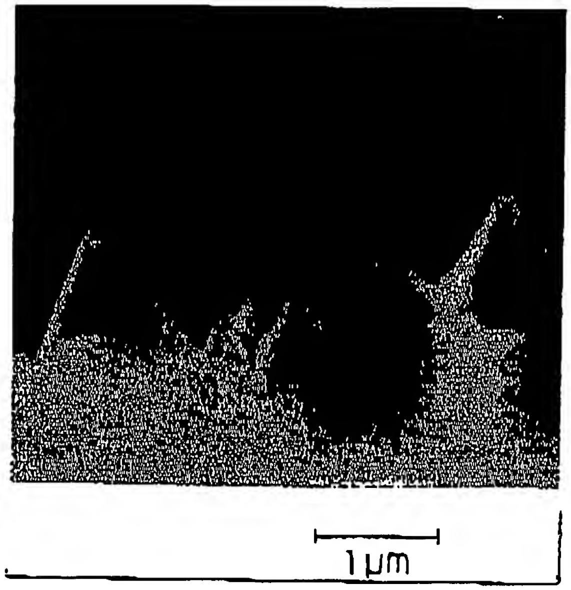


Figure 5-46 SEM photomicrograph of crystal-oriented Pb-8Sn-2Cu. "Side view" of deposit shows the pyramidal surface morphology that enhances wettability (defined in Section 6.6.1) by motor oil, which results in improved bearing performance. (*Advanced Materials & Processes*)

corrosion prevention. In Section 3.3 you learned about material characterization and may now wish to look back at Figure 3-17 to reexamine surface characteristic features. In the Ceramics Module you will read about additional surface engineering techniques such as diamond film and titanium coatings for cutting tools and other high friction/abrasion interfaces situations. Similarly, discussion in the Polymer and Composites modules deal with surface modifications to improve tribological characteristics and aspects of components.

The automotive industries' never ending quest to improve engine efficiencies continues to modify materials and materials surfaces. One such example involves the improved tribological aspects of sliding, plain bearings for automotive crankshafts. The modification involves a lead-alloy electroplated overlay. The goal of the improvement was to produce an overlay surface that would best retain lubrication. Thus an optimum surface is produced by controlling the crystallography of the electroplated alloy deposit. The solution was a designed surface morphology produced by controlling the orientation of the deposits with highly oriented crystal texture in primarily the [200] and [400] planes (refer back to Section 3.4.3). As seen in Figure 5-46, the Scanning electron microscope (SEM) photomicrograph reveals a surface of the overlay made up of relatively uniform, pyramid-shaped crystals approximately 1.5 μm across, having bases approximately 2 μm across.

5.10 FERROUS METALS

Iron and its many alloys, including cast irons and a nearly limitless variety of steels, comprise the ferrous metals group. Even with the wide acceptance of aluminum and polymeric materials, the iron-based alloys dominate all other materials in the weight consumed annually for manufactured products. Ten times more iron (mainly in the form of steel) is used than all other metals combined. Figures 5-47 and 5-48 show the processes that iron ore, coal, and limestone undergo in the production of iron. Coke is made from coal; many other products also come from this source.

5.10.1 Cast Iron

As shown in the iron–iron carbon equilibrium diagram (Figure 5 25), cast iron has between 2 and 4% carbon, compared with less than 2% for steel. Other elements in cast iron are silicon and manganese, plus special alloying elements for special cast irons. Many cast-iron products are used as they are cast, but others require changes in properties, which are achieved through heat treatment of the cast parts.

5.10.1.1 Gray cast iron. Gray cast iron is a supersaturated solution of carbon existing in a *pearlite* (two-phase structure) matrix. This carbon is mostly in the form of *graphite* flakes (soft form of carbon known as *elemented carbon*). It is the familiar metal used as the engine block of most automobiles and for other internal combustion engines. Figure 5-49 shows photomicrographs of two "as-cast" gray cast-iron specimens, one of low strength and one of medium strength. The amount of carbon, 3.2%, exceeds the solubility limits of iron, and the carbon precipitates out of solution with ferrite (carbon precipitates out in graphite form). Silicon (2%) is important in the *graphitizing* of gray cast iron. The graphite promotes machinability and lubricity of this metal. The damping ability of this alloy provides excellent absorption of vibrations and noise, which leads to its selection as piano sound-board frames and machine parts. These combined properties have also made gray iron a popular gearing material.

The ASTM system of designation for gray iron places it into classes 20 to 60 based on the minimum tensile strength for each class. For example, class 30 would have a minimum tensile strength of 30,000 psi (207 MPa), while a class 60 gray iron would be 60,000 psi (414 MPa). This classification is often preceded by "48" (ASTM A48 class 40), which designates the specification used to determine the mechanical properties of representative samples. Brinell hardness numbers (HB) range from 160 to 200 for ASTM 48 class 20 to 212 to 248 for ASTM 48 class 60. Machinability is a term used to attempt to describe the ease of machining steel to the size, shape, and surface finish required commercially. From this term comes *machinability rating* with cold-drawn B1112 grade steel rated at 100%. This standard test for B1112 machining requires turning with a suitable cutting fluid at 180 ft. per min. under normal conditions. All other steels are rated above or below this 100% level. Such ratings have proved to be undependable primarily due to unintended variations in the chemical content of steel. Further it must be pointed out that there is poor correlation between the hardness of steels and their machinability ratings. Gray cast iron is also available alloyed with nickel, chromium, and molybdenum to improve resistance to wear, corrosion, and heat while improving strength. Flame and induction hardening allow for increased surface hardness with a slightly tougher core.

5.10.1.2 White cast iron. Through slow cooling in sand molds, chilling of specific portions of a casting, and alloying, graphitic carbon is stopped from precipitating out of solution with the ferrite to produce a white cast iron. The name *white iron* comes from the white color produced in the fracture surface of the alloys. Figure 5-50 shows a photomicrograph of white cast iron to contrast with the photomicrograph of gray cast iron in Figure 5-49, which reveals graphite flakes. The carbon composition of 3.5% for unalloyed white iron has 0.5% silicon. The structure is an intermetallic compound of

a flowline of steelmaking

From iron ore, limestone and coal in the earth's crust to space-age steels — this fundamental flowline shows only major steps in an intricate progression of processes with their many options.

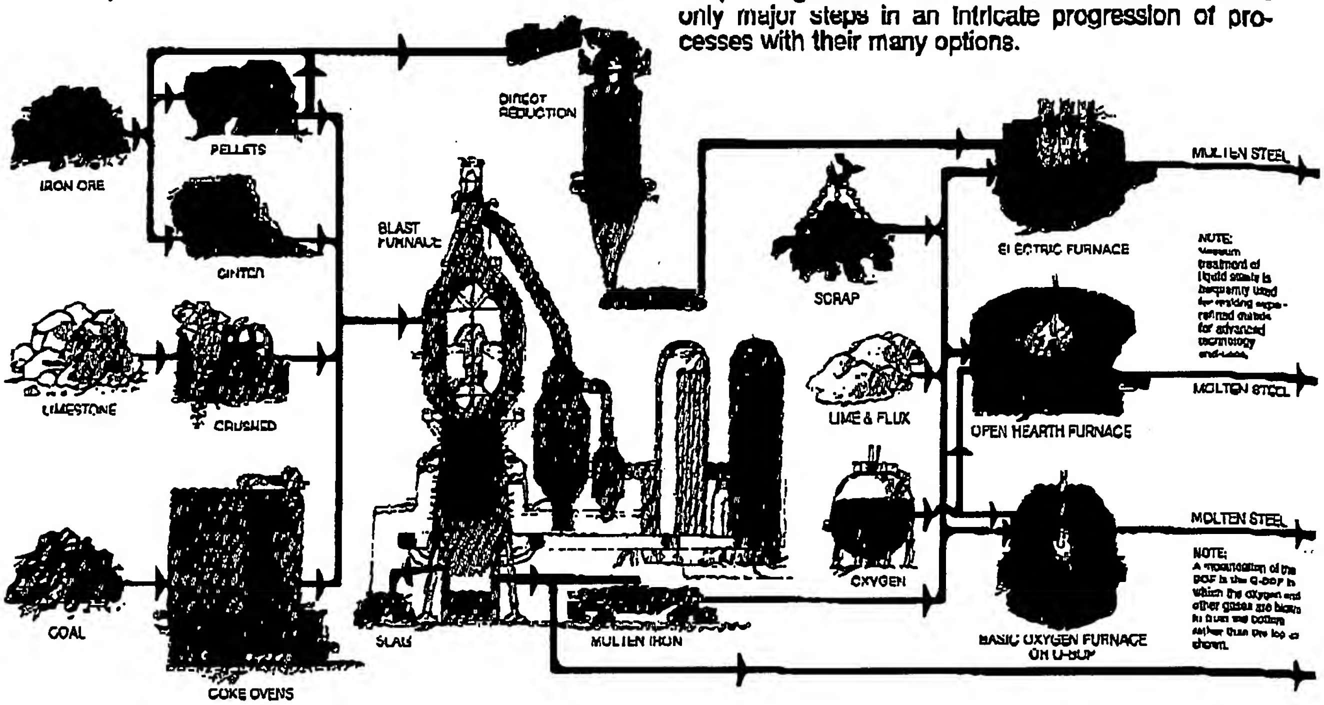


Figure 5-47 A flowline of steelmaking. (American Iron and Steel Institute.)

Figure 5-48 Molten iron rushes from a blast furnace through a series of clay-lined runners into a "submarine." Most of this iron will be charged in a molten state into basic oxygen furnaces for refinement into steel. Slag is tapped from a blast furnace several times during a cast and passes in an opposite direction into huge pots loaded on railroad cars for delivery to the slag dump. (Bethlehem Steel Corporation.)

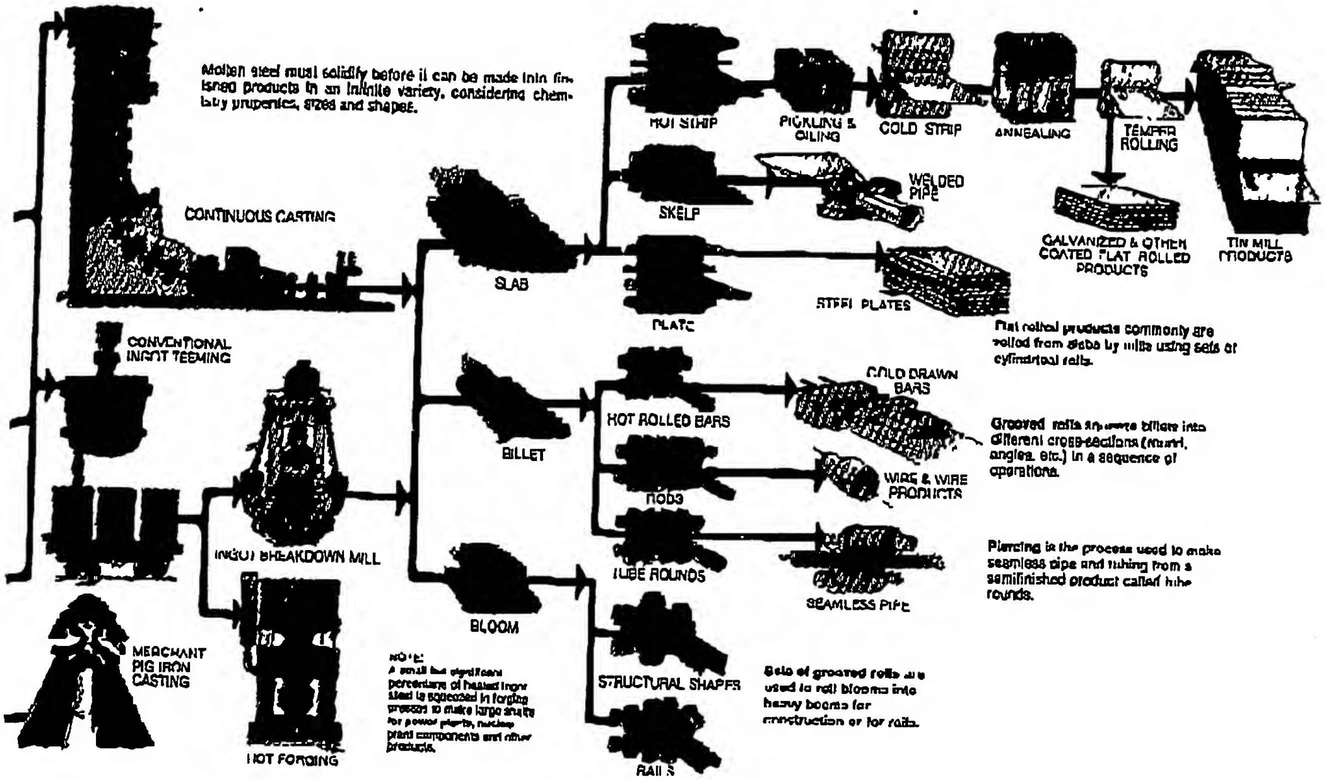
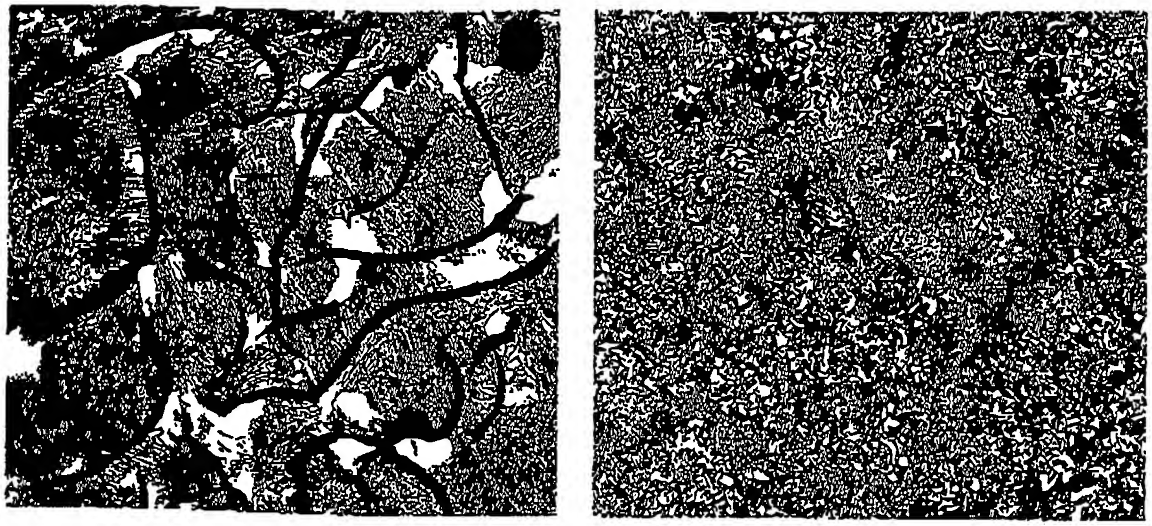


Figure 5-47 continued

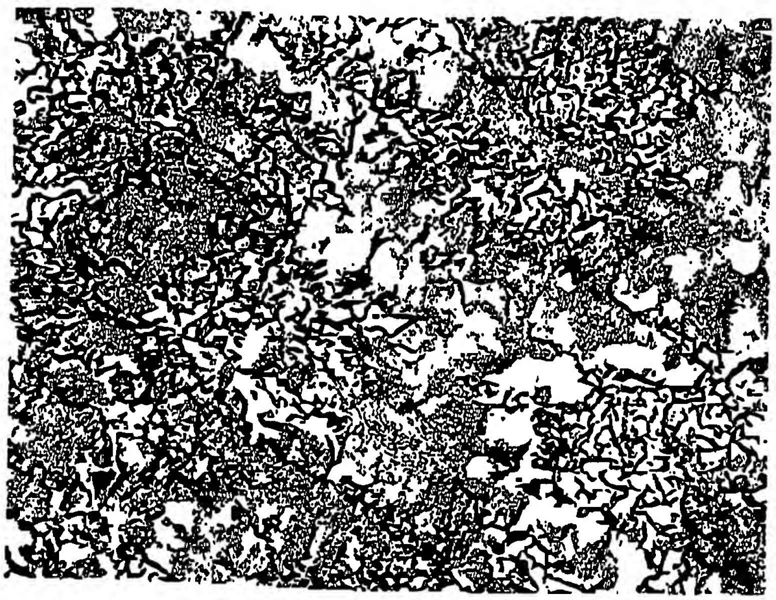
carbon and iron known as *cementite,* plus a layered two-phase solution of ferrite and cementite known as *pearlite*. The castings are very brittle, with Brinell hardness values from over 444 to 712. White cast iron has very good compressive strength above 200,000 psi (1380 MPa), with tensile strength around 20,000 psi, and good wear resistance; it finds applications as rolls for steel making, stone and ore crushing mills, and brickmaking equipment. This is generally the lowest-cost cast iron. Heat treatment can reduce brittleness, and as with gray iron, other properties are possible with alloying, but both of these add cost to the castings.

5.10.1.3 Nodular or ductile cast iron. With 3.5% C and 2.5% Si the addition of small amounts of magnesium (Mg), sodium (Na), cerium (Ce), calcium (Ca), lithium (Li), or other elements to molten iron will cause tiny balls or *spherulites* of graphite to precipitate out. As the name implies, the spherulitic structure improves the elongation or ductility while yielding superior tensile strength (150,000 psi or 1034 MPa) and machinability (similar to gray iron).

ASTM specifications for nodular iron indicate minimum tensile strength, minimum yield strength, and minimum percentage of elongation in 2 inches. For example, ASTM 120 90-02 would have a minimum tensile strength of 120,000 psi (828 MPa), minimum yield strength of 90,000 psi (621 MPa), and 2% minimum elongation in 2 inches (50.8 mm). In internal combustion engines, nodular iron finds application as crankshafts, rocker arms, and pistons. It is also used for cast gears, pumps, ship propellers, and with caustic-handling equipment. Although it is more expensive than gray iron in terms of weight, its specific strength makes ductile iron more economical, yet it lacks the damping ability and thermal conductivity of gray iron.



(a)



(b)

Figure 5-49 Gray cast iron. (a) The low-magnification photomicrograph at left illustrates the graphite distribution, type, and size. At 1000× (at right), the pearlite colonies and small ferrite grains adjacent to the graphite flakes are clearly distinguishable. The large round gray particles are manganese–sulfide inclusions. The surface of the specimen contains products of transformation of a faster cooling rate. (b) The distribution of fine graphite flakes in this sample results in an increase in strength of the iron. (Buehler Ltd.)

5.10.1.4 Malleable iron. The annealing of white iron castings causes nodules (large flakes) of soft graphitic carbon to form through the breakdown of hard and brittle cementite (Fe_3C). Two basic types of malleable iron are possible by varying the heat-treatment cycle. *Pearlitic malleable* iron is strong and hard, whereas *ferritic malleable* iron is softer, more ductile, and easier to machine. Malleable iron has 2.2% carbon and 1% silicon. In pearlitic malleable iron, 0.3 to 0.9% of the carbon is combined as cementite and allows for selective hardening of portions of a casting.

According to ASTM specifications A47-52 and A197-47, three grades are available: 35018, 32510, and cupola malleable iron. The 35018 and 32510 grades are ferritic, with the latter lower in silicon and consequently more ductile. Cupola malleable iron has a higher carbon and lower silicon content than the other grades, which yields lower strength and ductility. Basic properties for the three grades are shown in Table 5-1.

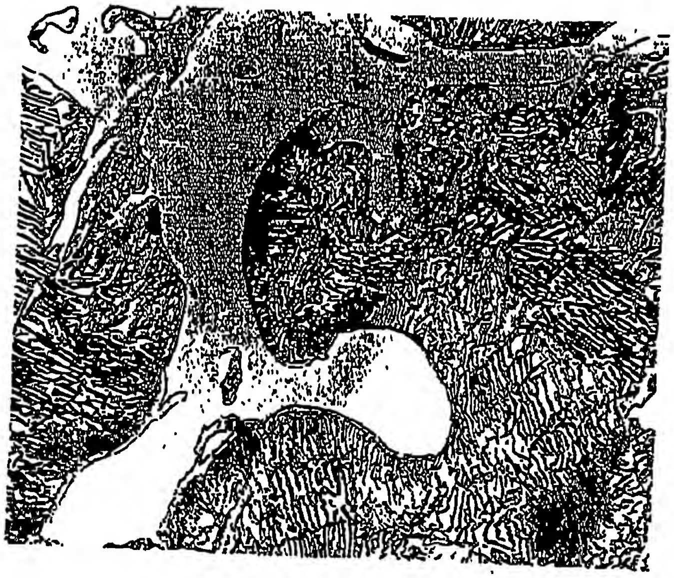


Figure 5-50 White cast iron. This specimen shows a hypereutectoid structure of pearlite and massive cementite. The dark areas are pearlite colonies surrounded by a network of cementite. At higher magnification, the alternate lamellae of alpha ferrite and Fe_3C are clearly resolved. (Buehler Ltd.)

Applications of the ferritic grades include in machined parts (120% machinability rating), automotive power trains, and hand tools such as pipe wrenches that take hard beatings. Applications for the stronger and harder pearlitic malleable iron include parts that require high surface hardness (up to HRC 60 or HB 163-269), such as bearing surfaces on automobiles, trucks, and heavy machinery.

Table 10.11 provides a comparison of properties of cast irons and wrought iron. As shown in the photomicrograph (Figure 5-51), *wrought iron* is an iron of high purity (less than 0.001 part carbon) with the slag (iron silicate) rolled or wrought into it. The ferrite matrix encloses iron silicate fibers shaped in the direction of rolling, which makes it an easy material to form. It is not a common metal today, but before the development of cast iron and steel making, a cruder form of wrought iron served society as weapons, tools, and architectural shapes. The Eiffel Tower in Paris was constructed of wrought iron in 1872.

5.10.2 Steel

As the most widely used engineering material, steel is available in an almost limitless variety. Several groups can be used, such as cast steel and wrought steel. Wrought steel covers the largest group and is the steel most common to consumers. Steel is cast into ingots when it comes from such steel-making processes as the open-hearth furnace or basic oxygen furnace. These ingots are processed further while in the hot "plastic" state

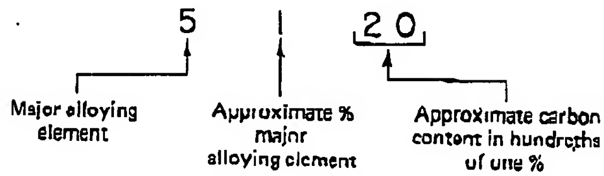
TABLE 5.1 PROPERTIES OF THREE CAST IRON GRADES

Grade	Minimum Tensile Strength [psi (MPa)]	Minimum Yield Strength [psi (MPa)]	Minimum Elongation [% in 2 in. (50.8 mm)]
35018	53,000 (365)	35,000 (241)	18
32510	50,000 (345)	32,500 (224)	10
Cupola	40,000 (276)	30,000 (206)	5

Figure 5-51 Wrought iron. The matrix of this specimen consists of ferrite grains similar to that of ingot iron. The elongated stringers are inclusions of slag composed largely of FeO and SiO_2. At higher magnification, small, dark particles within the ferrite grains are visible. These are finely dispersed impurities, apparent only after etching. (Buehler Ltd.)

to produce a variety of *wrought* or *hot-rolled steel* (HRS) products, such as bars, angles, sheet, or plate. Further working of HRS sheet or bar stock at below the recrystallization temperature of the steel is known as *cold working* or *cold finishing*. *Cold rolled steel* (CRS) is a harder steel because its grains have work hardened. Further classifications of steel are the carbon steels and alloyed steels.

The classification of steels takes a variety of forms. A very common system developed by both the Society of Automotive Engineers (SAE) and the American Iron and Steel Institute (AISI) uses four or five digits and certain prefix and suffix letters to cover many steels and steel alloys. As shown in Figure 5-52, the numbers reveal the major alloying element, its approximate percentage, and the approximate amount of carbon in *hundreds of 1 percent*, commonly called points of carbon. Table 5-2 shows the major groupings of carbon and alloy steels under the SAE–AISI classification. The alloy and carbon contents given in this four- or five-digit system are approximations. Complete specifications are available from SAE, AISI, or from handbooks such as *Machinery's Handbook* and Table 10-11. For example, the chromium–steel alloy 5120 has the following composition: C = 0.17 to 0.22%; Mn = 0.70 to 0.90%; Cr = 0.80 to 1.10%; P = 0.040%; and Si = 0.20 to 0.35%. Prefixes can indicate the process in making the steel, such as E for electric-arc furnace; and suffixes further clarify, for instance, H for hardenability guaranteed. Other societies, such as ASTM and ASME (American Society of Mechanical Engineers), have specifications for specialty steels, such as tool steels for dies, cutting tools, and punches or structural bolts and plates.



Examples:

Shown above chromium steel alloy with about 1% chromium and 0.20% (0.002 parts or 20 points) carbon

1015 — plain carbon steel with 0.15% (0.0015 parts or 15 points) carbon

E52100 — chromium steel alloy with about 20% chromium and 1 point carbon produced in an electric arc furnace

Figure 5-52 SAE–AISI steel designation.

TABLE 5.2 SAE–AISI SYSTEMS OF STEEL CLASSIFICATION

Digit Designation[a]	Types of Steel
10xx	Plain carbon
11xx	Sulfurized (free-cutting)
12xx	Phosphorized
13xx	High manganese
2xxx	Nickel alloys
30xx	Nickel (0.70%), chromium (0.70%)
31xx	Nickel (1.25%), chromium (0.60%)
32xx	Nickel (1.75%), chromium (1.00%)
33xx	Nickel (3.5%), chromium (1.50%)
34xx	Nickel (3.00%), chromium (0.80%)
30xxx	Corrosion and heat resistant
4xxx	Molybdenum
41xx	Chromium-molybdenum
43xx	Nickel–chromium–molybdenum
46xx	Nickel (1.65%), molybdenum (1.65%)
48xx	Nickel (3.25%), molybdenum (0.25%)
5xxx	Chromium alloys
6xxx	Chromium–vanadium alloys
81xx	Nickel (0.30%), chromium (0.30%), molybdenum (0.12%)
86xx	Nickel (0.30%), chromium (0.50%), molybdenum (0.20%)
87xx	Nickel (0.55%), chromium (0.50%), molybdenum (0.25%)
88xx	Nickel (0.55%), chromium (0.50%), molybdenum (0.35%)
93xx	Nickel (3.25%), chromium (1.20%), molybdenum (0.11%)
98xx	Nickel (1.10%), chromium (0.80%), molybdenum (0.25%)
9xxx	Silicon–manganese alloys

[a]x's indicate that numerals vary with the percentage of carbon in the alloy.

5.10.2.1 Carbon steel. This group of steels, also known as *plain carbon* and *mild steel*, dominates all other steels produced and is essentially iron and carbon with other elements that occur naturally in iron ore or result from processing. These elements are held to certain maximum levels: manganese (Mn), 1.65%; silicon (Si), 0.60%; and copper (Cu), 0.60%. Carbon steel may be cast or wrought. Typically, cast steels have more uniform properties since wrought steel develops *directional properties* as a result of rolling it into shape. See Table 10 11.

5.10.2.2 High-strength low-alloy (HSLA) steel. HSLA steel is a product of recent technology aimed at producing strong, lightweight steel at a price competitive with that of carbon steels. Although the price per pound of HSLA steel is greater than carbon steel, thickness is reduced due to a higher strength of 414 kPa (60,000 psi) versus 276 kPa (40,000 psi) for carbon steel; consequently, overall cost may be better for the HSLA, and significant weight savings are realized. The transportation industry, especially the automotive section, has employed HSLA in numerous structural applications. Although not as malleable as carbon steel, sheet HSLA steel could not be used in auto bodies, but a modification resulted in a dual-phase steel acceptable for the small bending radii required on auto bodies.

5.10.2.3 Alloy steel. The classification of alloy steel is applied when one or more of the following maximum limits are exceeded: Mg, 1.65%; Si, 0.60%; Cu, 0.60%; or through the addition of specified amounts of aluminum (Al), boron (B), chromium (Cr up to 3.99%), cobalt (Co), niobium (Nb), molybdenum (Mo), nickel (Ni), titanium (Ti), tungsten (W), vanadium (V), zirconium (Zr), or others. Alloy steels are grouped as low-, medium-, or high-alloy steel, with high-alloy steels encompassing the stainless steel group. Table 5-2 shows the SAE–AISI classification systems used for certain alloy steels. Elements added to steel can dissolve in iron to strengthen ferrites or α-iron (bcc) and form with carbon in the austenite or γ-iron phase (fcc) to produce carbides to improve hardness.

Chromium is effective in increasing strength, hardness, and corrosion resistance. Copper forms in austenite to reduce rusting. Manganese is an austenite former that, much like carbon, increases hardness and strength. Vanadium forms with ferrite to improve hardness, toughness, and strength. Molybdenum combines in carbide to improve high-temperature tensile strength and high hardness. Silicon dissolves in ferrite to improve electromagnetic properties, plus toughness and ductility. Nickel is an austenite former that both improves high-temperature toughness and ductility and provides rust resistance. Aluminum is effective as a ferrite former in reducing grain size, thus giving improved mechanical properties. Cobalt dissolves in austenite to improve magnetic properties and high-temperature hardness. Tungsten dissolves in ferrite to increase both hardness and toughness at elevated temperatures. Table 10-11 provides a comparison of selected alloys.

A recent example of the advances in the technology of alloy steels is AerMet 100, a nickel-cobalt alloy steel strengthened by carbon, chromium and molybdenum from Carpenter Technology Corp. The patented alloy with a designation, AMS (Aerospace Materials Specification) 6532 has an nominal analysis of 13.4 Co, 11.1 Ni, 3.1 Cr, 1.2

Mo, 0.23 C, with a balance of Fe. This alloy steel has the highest fracture toughness of any commercially available steel. Through heat treating it can obtain 1930-2700 MPa (280 300 ksi) tensile strength, and exceed a fracture toughness of 110 MPa · $\sqrt{m}$ at 1930 (100 ksi · in. at 280 ksi). Stress-corrosion cracking and fatigue resistance are two other good attributes. The superb combination of high strength and hardness coupled with high fracture toughness and ductility make it a superior alloy steel for applications that transcend the aerospace industry for which it was developed. Figure 5-53a shows one aircraft application of this steel's unique combination of properties that make it lighter, tougher, and reduced size without sacrificing strength.

5.10.2.4 Stainless steel. This group of high-alloy steels contains at least 10.5% chromium; it is more correctly called *corrosion-resistant steel* (CRES). The 10.5% chromium does not ensure that the steel will not rust; a sufficiently high content of carbon or other alloys may negate the passivity of the chromium (see Figure 5-53). As with other steels, stainless may be wrought or cast. Wrought stainless is grouped by its structure as ferritic, martensitic, austenitic, or precipitation hardening (PH). Cast stainless may be classified as heat resistant or corrosion resistant.

The ASTM and SAE along with other groups have developed the Unified Numbering System (UNS), a five-digit designation with an S prefix to replace the AISI designations for stainless steels. Stainless steels in the S30000 (AISI 300) series are nickel–chromium steels, while the S40000 (AISI 400) series have chromium as the major alloy. Series S20000 (AISI 200) are austenitic alloys, with manganese and nitrogen replacing some of the nickel—far less expensive alternatives when high formability and good machinability are not required. *Austenitic stainless steel* is a single-phase solid solution that has good corrosion resistance.

Martensitic stainless steels in the S40000 (AISI 400) series have high carbon content, up to 1.2%, with 12 to 18% chromium. The higher carbon content allows formation of more γ-iron, which quenches to a hard martensitic (up to 100%) steel, but the high carbon content reduces some of the corrosion resistance. If an austenitic stainless steel is heated sufficiently so that carbon precipitates out of solid solution as chromium carbide, which leaves less than 12% chromium in some segments of the alloy, it promotes intergranular corrosion.

The *ferritic stainless steels* have low carbon (0.12% or less) content and high chromium content (14% to 27%) in a solid solution and do not harden by heat treatment; they are in the S40000 (AISI 400) series and unlike martensitic and austenitic are magnetic. The ferritic grades have good formability, machinability, and corrosion resistance above martensitics. Specific properties of each type of stainless steel are found in standard references on steels. Table 10-11 shows selected stainless steels and their properties.

5.10.2.5 Other steel alloys. Beyond and including high-alloy steels and stainless steels previously discussed, there are a wide variety of specialty alloys. The ASM publishes a *Metals Handbook* of several volumes; *Volume I, Properties and Selection of Metals*, gives in-depth coverage on most metals. Included in the steel alloys is a range of tool steels, high-yield-strength (HY) steels, magnetic and electrical steels, ultrahigh-strength steel, maraging steels, low-expansion alloys, and ferrous powdered metals (PMs).